Assessment of energy consumption and carbon emission in plasma pyrolysis plant for eco-friendly waste treatment

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Abstract

A plasma pyrolysis plant of 50 kg/hr capacity is installed to investigate its energy consumption, carbon emission, and environmental safety performance. Municipal solid waste, precisely the dry combustible fraction, is processed at approximately 1000 ºC, utilizing plasma as the primary heat source. The resulting gas analysis indicated that CO and H_2 are the dominant combustible gases, constituting approximately 30% of the composition. A temperature shoot study is conducted to reduce the energy required for waste processing, revealing a total energy consumption of 0.586 kWh per kg of waste reduces the consumption by ~15 %. The Lower Heating Value (LHV) of the produced gas and cold gas efficiency is calculated to assess the technology's practicality, with promising results obtained. A mass and energy balance has been done to get a clear understanding of different products and by-product generation and heat losses during waste treatment. The ash generated during the process is characterized using Energy Dispersive X-Ray (EDX) analysis, suggesting its potential as a valuable raw material for construction sector.

Keywords: Municipal solid waste; Plasma pyrolysis; Energy consumption reduction; Carbon emission; Energy Dispersive X-ray (EDX).

1. Introduction

Municipal solid waste (MSW) is a sort of waste that people produce daily and is very common and highly complicated in composition. The substantial surge in waste production can be attributed to urbanization and industrialization. Projections indicate that waste generation in India will escalate to 161 million tons by the year 2041, amounting to five times the waste produced in 2001 (Annepu, 2012). Mass burn incineration has long been recognized as a prevalent thermal technology for MSW disposal (Brunner, 2017; Lombardi et al., 2015). There are over 1400 operational incineration plants worldwide, with numerous others in the commissioning phase as waste-to-energy solutions (Leckner, 2015). However, the overall energy efficiency of modern incineration plants remains low, typically ranging from 22 to 25%. This is primarily due to the maintenance of lower steam temperatures, typically up to 450°C, to protect components from corrosion caused by acidic gases like HCl (Panepinto et al., 2015). Consequently, the requirement for excess airflow limits the attainable temperature in the incineration process chamber, resulting in the generation of toxic pollutants, such as chlorinated dioxins and furans. These pollutants contribute to air pollution and are associated with severe health implications, including cancer and abnormalities (Central Pollution Control Board, 2016).

Although modern incineration plants are well equipped with the latest technology for environmentally friendly waste disposal, the risk of generating toxic gases is still debatable (Dong et al., 2018). The maximum chances of dioxin formation occur in the temperature range of 350 to 400°C (Masoumeh Safavi et al., 2021). To mitigate the adverse impacts of incineration, technologies such as pyrolysis, and gasification have emerged as viable alternatives. These processes have demonstrated the ability to reduce dioxin and furan generation to acceptable levels (Lopes et al., 2015). Among these,

gasification is considered more efficient for large-scale waste disposal. However, it also yields undesired byproducts, such as tar, alongside desired outcomes like syngas, producer gas, and char (Mbeugang et al., 2021). The presence of tar in the product gas can lead to numerous adverse effects, including reduced product quality, pipeline fouling, corrosion, and catalyst deactivation (Cortazar et al., 2023).

Thermal plasma technology stands out as the sole thermal waste treatment process capable of effectively treating various waste types, including hazardous materials, and converting waste to valuable products without affecting the environment (Gabbar et al., 2021; Yadav et al., 2023). It offers multiple advantages over conventional technologies, including high destruction efficiency (with volume reduction exceeding 99%), elimination of toxic molecules, reduced CO_2 emissions, and generation of high-calorific value gas (Li et al., 2016; Nema and Ganeshprasad, 2002). Plasma, as a high-temperature heat source, with charged particles, induces high reactivity within the atmosphere, facilitating tar decomposition reactions and enhancing the abatement rate of tar formation reactions (Bosmans et al., 2013; Rueda and Helsen, 2020). Thermal plasma technology has witnessed growing demand and installation in countries like the UK, USA, Canada, Belgium, and India, serving as a waste-to-energy technology for electricity generation of up to 100 MW capacity (Boulos and Mostaghimi, 2015). Plasma-assisted waste processing technology is broadly divided into plasma pyrolysis and plasma gasification. Plasma gasification occurs in a controlled amount of oxygen, while plasma pyrolysis may define as the decomposition of waste in an oxygen-starved environment (Central Pollution Control Board, 2016; Li et al., 2016; Munir et al., 2019). Consequently, In the thermal treatment process, an air requirement of $\leq$ 5% equivalent of stoichiometric air may be assumed to lead

toward pyrolysis conditions for waste processing (Pancholi et al., 2022).

Various lab-to-pilot scale studies have been conducted to investigate the impact of treating waste in plasma pyrolysis technology on the environment and output. A wide variety of waste, such as polyethylene, polypropylene, rubber, tires, biomass, paper, refuse-derived fuel, and medical waste, is treated using different power sources, for example, DC, AC, RF, and Microwave, where power supply capacity is used in a range of 0.8 to 50 kW, and in all instances, the primary combustible product composition is H_2 and CO. The concentration of pollutants such as CO_2 varies between 2 to 15%, while the solid residue in the form of carbon black, slag, or ash is found in a range of 6 to 40 % (Khongkrapan et al., 2014; Tang and Huang, 2010). Initially, Nema et al. have reported that energy consumption of approximately one kWh per kg is required for medical waste treatment using plasm pyrolysis technology in an eco-friendly manner (Nema and Ganeshprasad, 2002). Further Plasma Gasification Melting technology is used to convert MSW at 300 kg/h to syngas of 6 to 7 MJ/Nm^3, where steam feed rates vary in range of 70 to 100 kg/h, and plasma power varies between 0.8 to 0.87 kWh/kg (Zhang et al., 2012).

The stringent environmental regulations have created opportunities for plasma pyrolysis technology to emerge as a highly suitable option for treating MSW and other solid wastes, ensuring minimal environmental impacts. However, a thorough analysis of the existing article indicates a scarcity of research on applying plasma pyrolysis for treating solid wastes, particularly municipal solid waste. The available studies suggest that this technique offers several advantages, except for high energy consumption and maintenance demands. The existing plasma-assisted waste-to-energy technology consumes 0.8 to 1.2 kWh of energy treating per kg of solid waste,

excluding the energy required for subcomponents (Nema and Ganeshprasad, 2002; Tavares et al., 2019; Zhang et al., 2012). Thus, the plasma technology needs to reduce the energy consumption. Therefore, this study aims to investigate and propose a method to mitigate energy consumption specifically for MSW treatment.

An experimental study of temperature shoot inside the plasma chamber was carried out to examine the impact on energy consumption over an 8-hour period. The waste was processed within a predetermined temperature range of 850 to 1100 °C, considering environmental safety and limitations of refractory materials. This study replaced a continuous power supply with an intermittent power supply mode, allowing for energy recovery. A comprehensive analysis of overall carbon emissions during waste treatment was conducted, comparing the results with those from an incineration plant.

2. Materials and Methods

2.1 The Plasma pyrolysis setup

A pilot plasma pyrolysis plant is demonstrated in Jafrabad, Delhi, for MSW treatment. The capacity of the plant is 50 kg MSW per hour. It consists of several components such as shredder, conveyer belt, waste feeding hopper, primary chamber (plasma reactor), secondary chamber (combustor), quencher, venturi scrubber, demister, and chimney. The schematic diagram and image of the setup is shown in Figure 1(a).

The waste management process in a plasma pyrolysis plant involves a series of steps to convert MSW into useful products. The initial stage entails feeding the MSW into a shredder, which reduces the feedstock size to 5 to 10 mm. A waste feed hopper is connected to a conveyer belt, facilitating the transfer of the raw material into the primary chamber. Within the primary chamber, the waste

undergoes series of decomposition reactions, resulting in the conversion of the organic fraction into producer gas and the inorganic fraction into ash. Due to the lack of gas storage facility and generator, the gases are combusted in a dedicated combustor before being released into the environment. This combustion process ensures the immediate utilization of the gases. The flue gases produced subsequently undergo treatment in various gas cleaning equipment, including a quencher, venturi scrubber, and demister. These devices are employed to eliminate contaminants such as particulate matter, sulphur oxides, and acids from the flue gases.

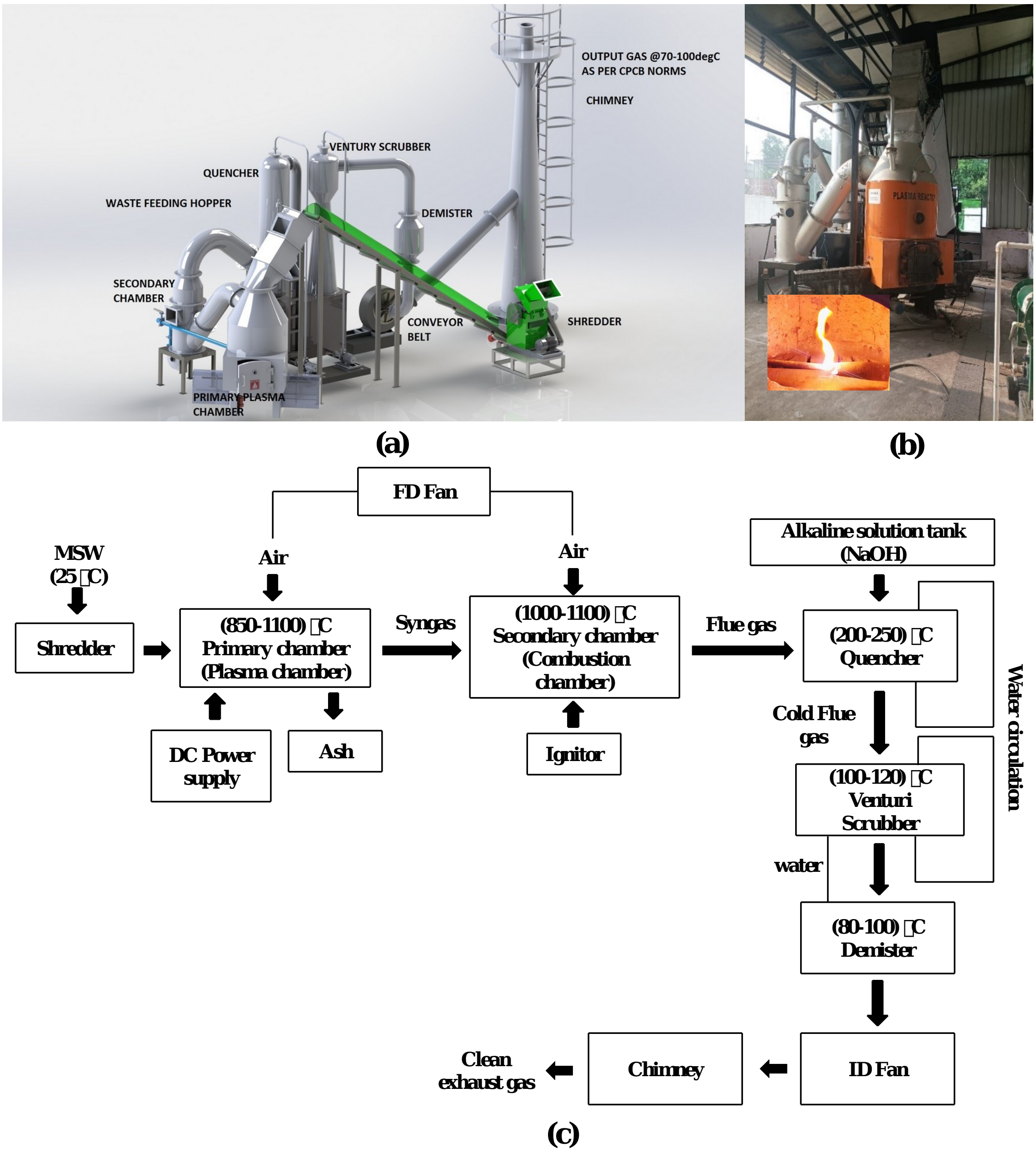


Figure 1. (a) The schematic diagram of the plasma pyrolysis plant (b) plasma generation inside reactor (c)Process flow diagram of waste processing in plasma pyrolysis plant.

Notably, the quenching process involves rapid cooling of the hot gases, reducing the chance of generation of toxic gas formation. Moisture present in the gas stream is removed by a demister, resulting in dry gases. These purified gases are then released into the atmosphere through a chimney or stack. The flow rate and

duration of the gases' stay (residence time) are regulated by induced draught (ID) fan. These fans ensure a controlled and steady flow of gases from the primary chamber to the stack. Figure 1(c) illustrates the detailed waste processing procedure employed in the plasma pyrolysis plant, providing a visual representation of the various stages and components involved.

The plasma reactor, act as a heart of the plasma pyrolysis system, bears resemblance to a fixed bed updraft gasification reactor in terms of its design. It consists of a two-electrode configuration and features an inlet port for the carrier gas (air) to facilitate plasma arc generation. The other essential components include a gas outlet port, a thermocouple port for temperature measurement, and an ash collector positioned at the bottom of the plasma reactor. The primary source of heat for waste processing within the reactor is the air plasma arc generated between the two graphite electrodes, one acting as the cathode and the other as the anode (Figure 1(b)). A DC power supply is connected to the graphite electrodes, allowing for a maximum current and voltage range of 300 A and 100 V, respectively. The electrodes are arranged in a horizontal free-burning linear configuration, while air, serving as the carrier gas (flow rate of 200 LPM), is introduced into the chamber perpendicular to the electrode gap. When the power supply initiates the electric arc, the carrier gas is ionized through collision processes (inelastic collisions, electron-impact ionization, radiative interactions, and charge exchange), transforming into plasma arc. Electron emission from the cathode is due to thermionic and field emission mechanism, which provides the high current necessary for plasma arc operation. The carrier gas also facilitates convective heat transfer towards the centre of the chamber, contributing to the decomposition of waste. To sustain the plasma arc with an extended plume length of around 20 cm, the maximum electrode gap is determined to be 5 cm. The

plasma arc generation commences at a current of 50 A and a gap of 5 mm between the electrodes. As the electrode gap increases, the voltage also increases, and the current is adjusted accordingly to maintain an optimum plasma state with adequate plume length and heat generation based on the supplied power.

2.2 Measurements

In the waste processing system, precise temperature measurements are essential for monitoring and controlling various components. To achieve this, a K-type thermocouple is installed in several components including the primary chamber, secondary chamber, quencher, venturi scrubber, scrubber water tank, ID fan, and chimney. The thermocouple for the primary chamber is positioned within the reactor wall. The specific placement of the thermocouple depends on the height between the chamber bottom and the thermocouple itself. In cases where the height (H) is less than 1 m, the thermocouple is embedded within the refractory material to prevent any potential damage and ensure accurate temperature measurements (Zhang et al., 2012).

The measurement and analysis of various gas parameters in the waste processing system are vital for effective monitoring and compliance with environmental standards. To assess the airflow rate, glass tube rotameters with a range of 100 to 2000 LPM are installed aligning air blower. For the analysis of producer gas composition, a sample is collected between the primary and secondary chambers. To facilitate this, a gas compressor is connected to the collection port, enabling the sample to be stored at a pressure of 4 to 5 bar in a cylinder of 2 kg capacity. The gas sample is then subjected to analysis using a Pollutek syngas analyser (3100P). This instrument allows for the determination of the precise composition of the producer gas. To ensure continuous monitoring of exhaust gas quality for environmental safety, an online monitoring device is

strategically connected to the chimney. This device is compliant with the regulations set by the Indian central pollution control board (CPCB) and is equipped with an alarm system. It continuously measures and monitors the exhaust gas quality, providing real time data to mitigate any potential environmental risks and ensure adherence to environmental safety standards.

2.3 Feedstock (MSW)

The feedstock used for processing is the waste collected from society and the local market. These piled wastes are initially segregated into trommel, and only dry combustible fractions, such as paper, plastics, styrofoam, textile, rubber, leather, etc., are processed. The waste sampling is done as per the standard conning and quartering method to determine the sample composition (Alakangas, 2015). The composition of the sample is Plastic and styrofoam (53%), paper and cardboard (18%), textile (26%), rubber and leather (3%) and inert (2%). The proximate & ultimate analysis and calorific value results are shown in Table 1.

Table 1: Proximate & ultimate analysis, the calorific value of the feedstock

Proximate analysis	
Moisture content (%)	*7.91*
Volatile matter (%)	*67.69*
Ash content (%)	*21.95*
Fixed carbon (%)	*2.45*
Ultimate analysis	
Carbon (%)	*57.86*
Hydrogen (%)	*4.65*
Nitrogen (%)	*0.44*
Sulphur (%)	*0.19*
Oxygen (%)	*14.92*
Calorific value	
High calorific value (MJ/Kg)	*25.40*
Low calorific value (MJ/Kg)	*24.38*

The proximate and ultimate analysis of the selected samples is done for the waste characterization study. The sample qualifies the criteria of waste-to-energy application since it follows all the parameters of Indian CPCB guidelines, such as volatile matter should be more than 45%, the calorific value should be > 1200 kcal/kg, fixed carbon < 15% and total inert < 35% (Central Pollution Control Board, 2020).

3. Results and Discussion

3.1 Feedstock properties

The chemical formula of feedstock helps us understand the parameters required for efficient waste processing. The airflow needed for complete combustion in the combustion chamber is calculated using stoichiometric calculation of the chemical formula. Mole fraction calculation and normalization of obtained value to the carbon give the chemical formula of feedstock. Mole fraction is calculated by dividing the mass percentage value of respective elements by their atomic weight, and normalization is done by dividing the mole fraction values of elements by carbon (Ibrahim, 2020). The estimation of the mole fraction and normalized value with and without moisture is shown in Table 2. Since the waste incoming for processing holds moisture within it, the chemical formula is also formulated considering the same condition, and hydrogen and oxygen contents are added to the respective element's mass percentage and used for further analysis.

Table 2: Chemical formula of feedstock

Parameters	Without moisture					With moisture				
	C	H	O	N	S	C	H	O	N	S
Mass percentage	57.8	4.65	14.9	0.44	0.19	57.8	5.52	21.96	0.44	0.19
Atomic weight	12	1	16	14	32	12	1	16	14	32
Mole fraction	4.82	4.65	0.93	0.03	0.006	4.82	5.52	1.372	0.031	0.006

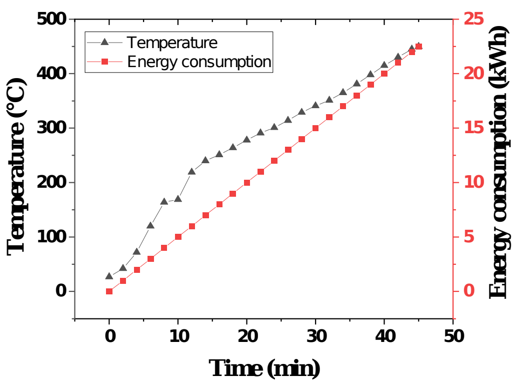
Normalization	1	0.96	0.19	0.006	0.001	1	1.08	0.285	0.006	0.001
Chemical composition (without moisture)						$CH_{0.964}O_{0.193}N_{0.0065}S_{0.0012}$				
Chemical composition (with moisture)						$\boldsymbol{CH_{1.082}O_{0.285}N_{0.0065}S_{0.0012}}$				

3.2 Temperature shoot study in the primary chamber for energy consumption reduction

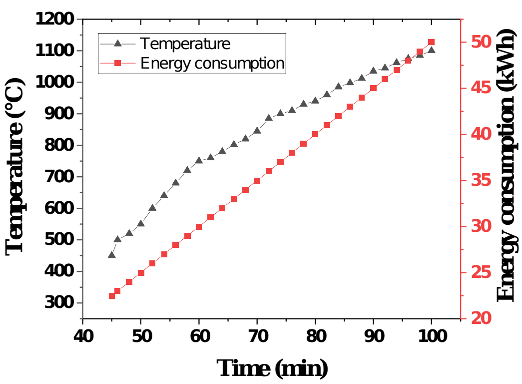
The energy consumption for waste treatment using plasma pyrolysis technology is comparatively higher than conventional technology, a known barrier to technology commercialization. This study is conducted to reduce the input energy during waste treatment. The primary chamber is preheated keeping power supply fixed (30 kW) until its wall temperature reaches 450 °C, and it takes around 45 minutes to attain the same with energy consumption of 22.5 kWh. The preheating process is kept for a limited time and temperature because of the power supply capacity and time constraints. It is possible to achieve higher temperatures during preheating, but it requires more than 4 hours (Sharma et al., 2020). The detailed change in temperature and energy consumption during preheating is shown in Figure 2(a). After preheating, waste fed into the chamber with a continuous power supply, which rapidly increases the chamber temperature. The continuous heat generation from waste and power supply, the chamber achieved temperature of 1100 °C within 55 minutes. The total energy consumed up to this duration is 50 kWh. The details of change in temperature and energy consumption with time is shown in Figure 2(b). The maximum limit of the installed chamber's refractory material (ceramic wool and refractory brick) is around 1700 °C. To avoid any damage to refractory material and environmental safety regarding toxic gas generation, the operating temperature is set to 850 to 1100 °C. This study considers the upper limit of waste processing temperature as

temperature shoot. The reason behind the temperature shoot is the continuous devolatilization of waste during pyrolysis reactions and high-density heat energy generation from plasma. As the temperature surpasses the upper-temperature limit, the sensors in the power supply panel (to detect the temperature with the help of a thermocouple) auto-cut the power supply to the plasma chamber. The plasma chamber is operated with continuous waste feeding without any power supply until the temperature reduces to the lower limit.

Pyrolysis reactions of waste includes endothermic and exothermic, where initially energy is consumed to devolatilize waste, and simultaneously energy released because of exothermic reactions. It has been observed that waste processing without feeding power during temperature shoot can sustain the chamber temperature within the operating condition for a certain time period. Since power is not supplied during temperature shoot, the energy consumption is zero ultimately reduces the input energy required for waste treatment. As shown in figure 3(a), where the energy consumption didn't change between 100 and 110 minutes, and the temperature



(a)

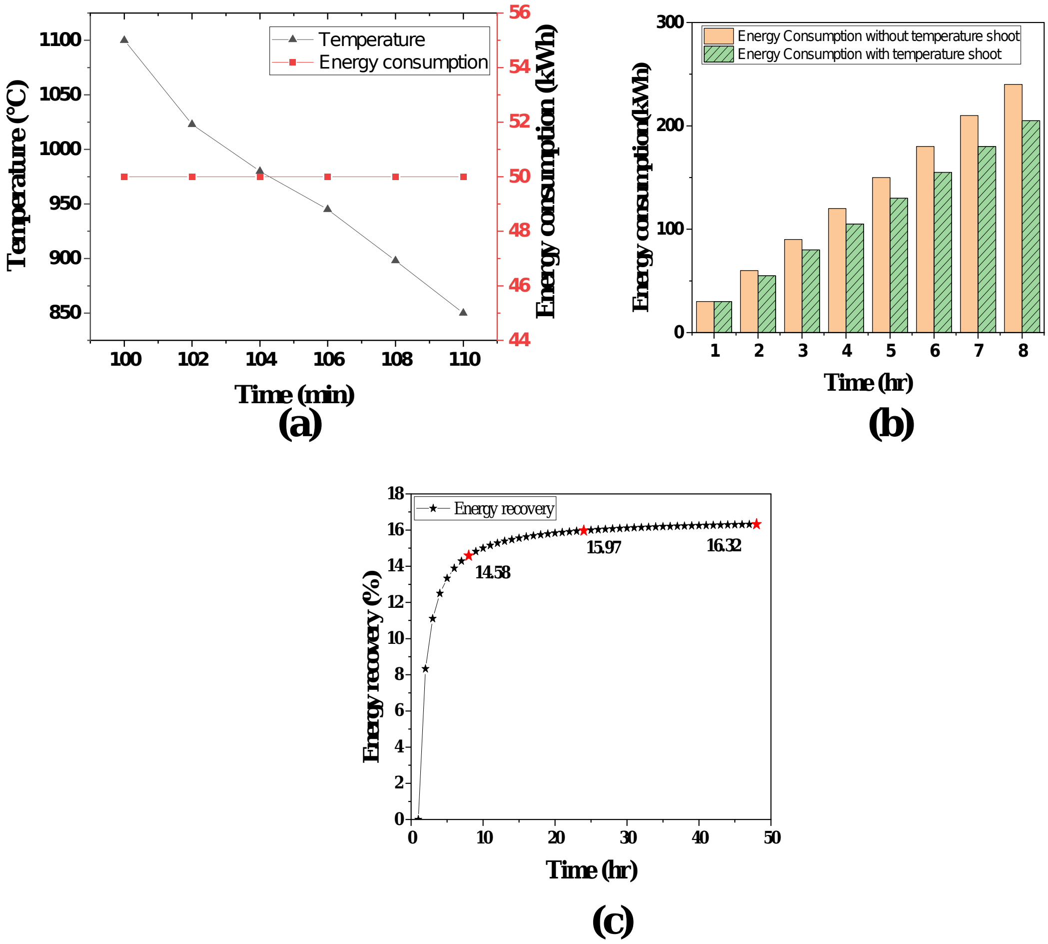


(b)

drops from 1100 to 850 °C in about 10 minutes. During this time, energy consumption, which should be 5 kWh (30 kW fixed DC plasma power supply) is recovered.

Figure 2. (a) Preheating of the plasma chamber (b) Waste treatment into plasma chamber up to upper limit operating temperature condition

The temperature shoot study is done several times and compared with continuous power supply conditions for waste processing. This temperature shoot process occurs every hour of waste processing. It has been observed that the chamber has the capability to sustain the operating temperature for approximately 10 minutes without a power feeding. The timing gap between the two temperature shoot



cycles is not fixed, and the reason behind this may be waste composition complexity and energy loss. The comparative study with continuous power supply and temperature shoot is shown in Figure 3(b). The energy consumption for first hour is same in both cases since temperature shoot would not take place, after it every next hour there is a reduction in energy consumption following 8.33%, 11.11%, 12.5%, 13.33%, 13.89%, 14.28%, 14.58% for next seven hours of waste processing as shown in Figure 3(b)

Figure 3. (a) Energy recovery during waste treatment in the plasma pyrolysis chamber (b) Comparative study of Energy consumption with and without temperature shoot (c) Optimization of energy recovery with respect to operation time.

Generally, for treating one kg of plastic waste in a plasma pyrolysis plant, 1 kWh per kg of energy is required, excluding the energy requirement for subcomponents and heat losses from the chamber (Central Pollution Control Board, 2016). Regarding MSW treatment, literature reported energy consumption of around 0.8 to 1.2 kWh excluding subcomponents (Tavares et al., 2019; Zhang et al., 2012). As per the energy consumption analysis shown in Figure 3(b), the total energy consumed during eight-hour operations is 205 kWh for 350 kg of waste treatment, which is 0.586 kWh per kg waste, while in the case of continuous power supply, it is 240 kWh that is 0.686 kWh per kg waste.

As a result, it might be inferred that the primary chamber's temperature shoot study recovers around 15 % of the energy input used to process MSW in 8-hour operation. Similarly, the energy recovery percentage for 24 and 48 hours of continuous operation has been calculated and found 15.97 % and 16.32 % respectively as shown in Figure 3(C). The analysis results demonstrate minor differences in energy recovery as compared to the 8 hours of operation (14.58 %) so it may conclude that the best possible energy recovery from temperature shoot study is around 15 %.

3.3 Analysis of carbon emission from waste treatment

The effectiveness of conventional waste treatment systems is hampered by the emission of millions of tonnes of carbon during thermal waste treatment. To study the carbon footprint of plasma pyrolysis technology and its benefits in comparison to the conventional waste treatment technologies, various parameters,

including airflow rate, producer gas composition, and exhaust gas quality, are studied, and a significant reduction in carbon footprint is observed.

3.3.1 Air flow rate for primary chamber

The purpose of the air supply in the primary chamber is solely for plasma generation. Generally, incineration requires stoichiometric air; gasification requirements vary between 20 to 30 % of stoichiometry, while pyrolysis occurs in starved air (≤ 5 % stoichiometry) conditions (Nega et al., 2022). Since the calculated molecular weight of the sample is 17.77 kg, the stoichiometric or theoretical air calculation yields an air requirement of 8.72 kg per kg MSW and produced approximately 2.5 kg of CO_2. The detailed stoichiometric air calculation is given in Table 3. Considering stoichiometric air calculation and pyrolysis process criteria (air requirement of ≤ 5% equivalent of stoichiometric), the air is supplied in the primary chamber at rate of 200 LPM, approximately 3% of the required stoichiometric air.

Table 3: Stoichiometry air required calculation

Reactant		Product			
$CH_{1.082}O_{0.285}N_{0.0065}S_{0.0012}$	$1.129(O_2+3.76N_2)$	CO_2	$0.54H_2O$	$0.0012SO_2$	$4.25N_2$
17.77 kg	155 kg	44	9.72	0.076	119
1 kg	8.72	2.47	0.63	0.005	6.69

3.3.2 Producer gas composition

A sample of the product gas generated in the primary chamber is carefully collected within a compressed chamber maintained at a pressure of 4 to 5 bar. This sample is subsequently subjected to gas composition analysis for comprehensive characterization. To conduct

the analysis, a syngas analyser (model 3100P) is employed. The product gas is introduced into the analyser through its intake port at a controlled flow rate of 1 LPM. The determined gas composition is of great significance as it closely aligns with the findings of prior experimental and theoretical studies reported in the existing literature (Gitano-Briggs and Kean, 2016; Zhang et al., 2023). The composition of the product gas, as established through the analysis, is as follows: hydrogen (H_2) content at 9%, carbon monoxide (CO) at 21%, methane (CH_4) at 3%, nitrogen (N_2) at 59%, and carbon dioxide (CO_2) at 8%. The lower heating value (LHV) of gas is calculated based on the producer gas composition. LHV may define as the total heat released during the complete combustion of a fuel, and it may calculate using the following expression (Roberta and Barbalace, 2003).

$$LHV_{product\ gas} = 10.79\ Y_{H2} + 12.63\ Y_{CO} + 35.83\ Y_{CH4} \quad (1)$$

where Y_{H2},Y_{CO},Y_{CH4} are the percentage of gas in the composition of product gas, $LHV_{productgas}$ is the lower heating value of product gas (MJ/Nm^3). The LHV of gas is calculated following equation 1 and found 4.7 MJ/Nm^3. However, previous articles reported a 5 to 10 MJ/Nm^3 range of LHV with steam and oxygen supply conditions (Bhatt et al., 2022; Chen et al., 2014). The heating value can be considered in the range of reported literature since steam is not supplied to the chamber in this study. It would be possible to improve by including high-temperature steam in the primary chamber.

3.3.3 Air flow rate for secondary chamber

The purpose behind the secondary chamber installation is to combust the producer gas and protect the environment from harmful gases such as CO, CH_4, etc, generated during waste pyrolysis (as gas storage facility is not available). A gas combustion chemistry equation is used to calculate the airflow rate needed for the complete combustion of producer gas (Gitano-Briggs and Kean, 2016). From balancing of carbon, hydrogen, oxygen, and nitrogen in equation 2, we have a, x, y, and z as 0.21, 0.32, 0.15, and 1.3796, respectively. The calculated molecular weight of producer gas is 26.58 kg for which it required approximately 29 kg of air and generates 14 kg of CO_2, similarly for one kg of producer gas approximately one kg of air is required, and it will produce around half kg of CO_2. The detail of the stoichiometric combustion is mentioned in Table 4.

$$0.09\ H_2 + 0.21\ CO + 0.08\ CO_2 + 0.03\ CH_4 + 0.59\ N_2 + a\ (O_2 + 3.76\ N_2) = x\ CO_2 + y\ H_2O + z\ N_2 \quad \text{----(2)}$$

Table 4: Stoichiometric air required for combustion of product gas

Reactant		Product		
Producer gas	0.2 (O_2 + 3.76 N_2)	0.32 CO_2	0.15 H_2O	1.3796 N_2
26.58 kg	28.829 kg	14.08 kg	2.70 kg	38.63 kg
1 kg	1.08 kg	0.53 kg	0.1 kg	1.45 kg

Based on the analysis conducted, the research setup under investigation demonstrates a CO_2 production rate of approximately 0.5 kg per kg of waste processed. In contrast, an incineration unit would generate approximately 2.5 kg of CO_2 per kg of waste, as depicted in Table 3. The comparison of carbon emissions between incineration and plasma pyrolysis, indicates a substantial reduction of up to 80%. These findings lead to the conclusion that the implementation of waste treatment in plasma pyrolysis plants holds significant potential for reducing the overall carbon footprint.

3.3.4 Cold gas efficiency (CGE)

Cold gas efficiency is a standard parameter through which the energy efficiency of the waste treatment process can be determined (Qinglin et al., 2009). Here it is used to determine the same in the case of plasma pyrolysis.

$$\text{CGE (\%)} = \frac{\dot{m}_{product\,gas} \times LHV_{product\,gas}}{\left(\dot{m}_{MSW} \times LHV_{MSW}\right) + Power\,supply} \quad \text{-------------------- (2)}$$

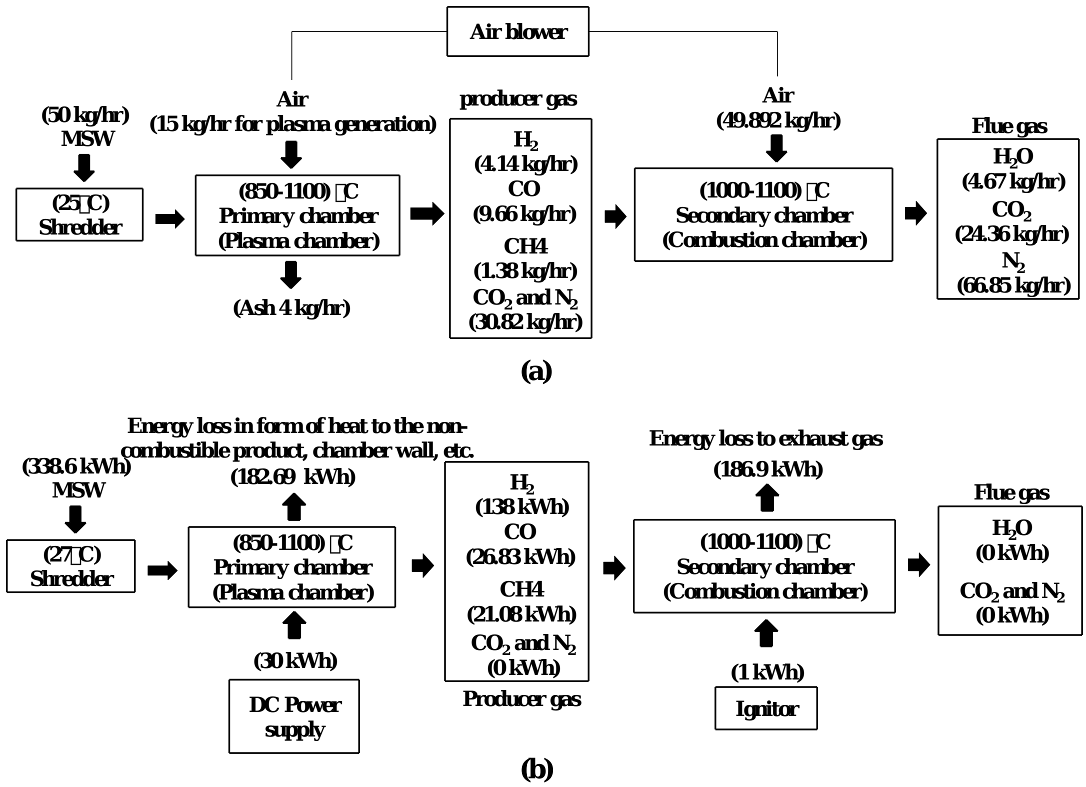
where $\dot{m}_{product\,gas}$ is mass flow rate of product gas (m^3/kg), $LHV_{product\,gas}$ is the lower heating value of product gas (MJ/Nm^3), $\dot{m}_{MSW}$ is mass flow rate of MSW feed (kg), and LHV_{MSW} is a lower heating value of MSW (MJ/kg). As per the previous studies, the gas flow rate from the treatment of one kg of solid waste (MSW, plastic, rubber, etc.) is 0.6 to 3.5 m^3 in plasma gasification/pyrolysis (He et al., 2010; Rutberg et al., 2013). For our setup, the product gas flow rate is measured using a gas flow meter and found 2.5 to 3 m^3/kg of MSW. Variation in gas flow rate is due to the complex nature of MSW composition and in higher range because of more plastic contents. Cold gas efficiency is calculated considering an energy consumption of 0.586 kWh per kg waste, feed @ 50 kg/hr, and LHV of MSW and producer gas is 24.38 MJ/kg (6.77 kWh) and 4.7 MJ/m^3 (1.3 kWh) respectively, resulting in a range of 44 to 53 %. However, the CGE reported by other researchers is 30 to 70%, and the efficiency of more than 60% is mainly with steam plasma pyrolysis/gasification (Ganza and Lee, 2023; Mazzoni and Janajreh, 2017). Based on the information provided in published articles, it can be inferred that the cold gas efficiency of plasma pyrolysis technology meets the specified compliance standards.

3.3.5 Mass & Energy balance

A mass and energy balance are performed to demonstrate how products are generated stepwise and the losses associated with the

waste process. It is assumed that during plasma pyrolysis of waste, the organic fraction is completely converted into gas while the inorganic fraction gets converted into ash, which is ~ 8%, approximately 4 kg by weight. It is also assumed that the plasma chamber air supply will be consumed entirely for plasma generation. The LHV of 24.38 MJ/kg (338.6 kWh/50 kg) of MSW sample provided in the proximate and ultimate analysis test data (Table 1) is considered during analysis. As per the mass balancing analysis the air requirement in primary plasma chamber and secondary chamber is 15 kg and 50 kg per hour respectively. The mass and energy balance in detail are shown in 4 (a) and (b).

Here tar formation is not considered since it is assumed that extremely high-temperature plasma as a heat source reduces the chance of tar formation by reducing the reaction of tar formation or



cracking of tar into gas (Tavares et al., 2011). The calorific value of combustible gases such as H_2, CH_4, and CO are taken as 120, 55, and 10 MJ/kg, respectively. From energy balancing analysis, it is observed that 185.91 kWh is produced in form of producer gas which is approximately 50 percent while other 50% of energy supplied to the chamber is lost in from generation of non-combustible gases such as CO_2 and N_2 and non-combustible byproduct such as ash, and heat loss to the chamber wall.

Figure 4 (a). Mass balance for waste treatment in plasma pyrolysis plant (b). Energy balance for waste treatment in plasma pyrolysis plant

3.4 Influence of plasma pyrolysis waste treatment on the Environment

Thermal waste treatment methods can have adverse environmental implications, including the emission of pollutants into the atmosphere, elevated carbon concentrations in fly ash, and wastewater generation during exhaust gas treatment. In contrast, the application of eco-friendly waste treatment in plasma pyrolysis plants offers a promising alternative. Extensive testing of exhaust gas, ash, and wastewater samples derived from plasma pyrolysis treatment has yielded favourable results, indicating its potential as an environmentally friendly waste treatment solution.

3.4.1 Characteristics of exhaust gas from waste treatment

Exhaust gas samples were systematically collected and subjected to testing in accordance with the prescribed standards set by the CPCB India. The specific results obtained from this analysis are presented in Table 5. The pollutant concentrations, including particulate matter (PM), sulphur oxides (SO_X), and nitrogen oxides (NO_X), were found to be significantly lower than permissible limits (Central Pollution Control Board, 2017). Specifically, PM exhibited a reduction of 49.80 %, while SO_X and NO_X concentrations were reduced by 91.25 % and 85 %, respectively. Furthermore, the concentration of carbon monoxide (CO) in the exhaust gas was notably reduced by 99 % compared to the permissible limit. These results affirm the effectiveness of the waste treatment process in mitigating pollutant emissions, ensuring compliance with environmental standards, and emphasizing the suitability of releasing the exhaust gas into the open environment.

Table 5. Pollutant Emission report of exhaust gas from plasma pyrolysis plant.

Sl. No.	Parameters	Test method	Results	Units	Limit
1.	Particulate matter (PM)	IS:11225 (part 1)	49.80	mg/Nm^3	100

2.	Nitrogen dioxide (NO_2)	IS:11225 (part 7)	35	mg/Nm^3	400
3.	Carbon monoxide (CO)	USEPA Method no. 10	0.01	1 % by volume	1
4.	Sulphur dioxide (SO_2)	IS:11225 (part 2)	30.40	mg/Nm^3	200

3.4.2 Characteristics of Ash from plasma treatment of Waste

Ash generates continuously during plasma pyrolysis of MSW with a small percentage of ~8 % (4 kg/hr) by mass. The produced ash in the primary chamber accumulates in the ash collector. The ash samples are tested to know the elemental composition and possibility of further utilization as a raw material. Energy Dispersive Xray (EDX) testing is used for the elemental composition of ash, whose details are shown in Figure 5. The primary composition of ash is oxygen, calcium, and silicon, and other elements like Mg, Cl, Na, Al, Fe, S, K, Ti, and P are comparatively less. Silicon and calcium make the sample a valuable by-product since these are the significant components of ash brick. For decades, fly ash has been used as a raw material in the concrete industry. Ashes have various potential applications, such as raw material in ash brick manufacturing, road construction, membrane for wastewater treatment, and other processes such as zeolite synthesis, soil stabilization, catalysis, valuable material recovery, etc (Mushtaq et al., 2019). According to the previously reported studies, significant unburned carbon in the available ash samples prevents fly ash from being used. The typical range of unburned carbon in ash is 2 to 12 % (Ahmaruzzaman, 2010). Fly ash's increased proportion of unburned carbon causes efficiency loss and low marketability for the raw material in concrete making (Hower et al., 2017). The restriction in air-entraining agent absorption eventually lowers the quality of concrete in terms of freeze-thaw durability and workability, ultimately preventing fly ash

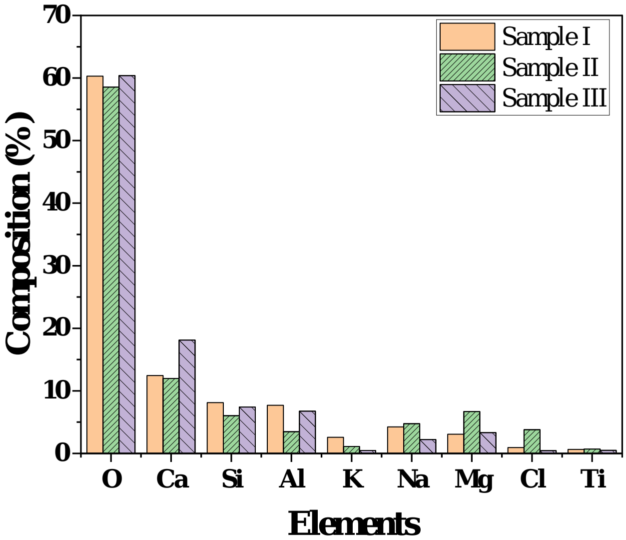
as a substitute for cement (Bartonova et al., 2011). The ash produced in plasma pyrolysis technology found approximately carbonless.

Figure 5. Ash elemental composition from plasma pyrolysis technology

4. Conclusions

This study highlights the advantages of utilizing a pilot-scale plasma pyrolysis technology for the treatment of municipal solid waste:

- The MSW of a lower heating value, 24.38 MJ/kg, is converted into



  a producer gas of 4.7 MJ/Nm^{3}, and the cold gas efficiency of the plant is 44 to 53 %.
- Temperature shoot study reduces energy consumption by approximately ~15 %.
- Carbon emission analysis results in 80% lower in comparison to the incineration pant.
- The ash produced as a solid residue is carbonless and may recommended as a raw material for the construction sector.

Credit authorship contribution statement

Tejashwi Rana: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing - original draft. **Satyananda**

Kar: Conceptualization, Validation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing interest.

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